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Exclusive π°- and η-meson production in ^{40}Ar + $^{\mathrm{nat}}$Ca at 800A MeV

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Abstract

The impact-parameter dependence of π°- and η-meson production is reported for the system ^{40}Ar+$^{\mathrm{nat}}$Ca at a beam energy of 800A MeV. Scaling of the meson abundances with the transverse mass is observed. The experimental results are compared to calculations within the BUU model. © 1997 Elsevier Science B.V.

The investigation of meson production in heavy-ion collisions is a sensitive tool to study the hot and dense nuclear matter formed during the collision. Pions and η mesons are mesonic probes available in the 1–2A GeV energy regime. While pions mainly originate from the decay of the $\Delta(1232)$ resonance, η mesons are almost exclusively produced through the decay of the N(1535) resonance [1]. Although both kinds of mesons are produced through the excitation of different baryon resonances, scaling of the meson yields with the transverse mass has been recently observed for the Ar+Ca system at 1.0 and 1.5A GeV [2], i.e. at energies slightly above and below the η threshold in free nucleon-nucleon collisions. The validity of this scaling law at beam energies substantially below the η threshold is still an open question for medium size systems. Additional information about meson-production mechanisms can be obtained from a study of the impact-parameter dependence of the production of both mesons.

It is in this spirit, to investigate the persistence of

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the m_t-scaling law and the different production mechanisms of π^0 and η mesons as a function of the impact parameter in medium size systems, that the present investigation has been undertaken. In this letter we report on subthreshold η-meson production for the system ^{40}Ar+$^{\mathrm{nat}}$Ca at 800A MeV, where, for the first time, results on η meson production as a function of the impact parameter are obtained simultaneously with π^0-meson data.

The experiment was performed at the heavy-ion synchrotron SIS at GSI Darmstadt. Neutral mesons were identified by an invariant-mass analysis of photon pairs. In order to detect these photons the TAPS detector was used [3–5]. This spectrometer comprised 384 telescopes composed of a BaF_2 crystal preceded by a plastic-scintillator veto detector to tag charged particles (CPV). The individual detectors were arranged in six blocks of 64 modules each. These blocks were mounted in two towers which were placed at polar angles of $\pm 57°$ with respect to the beam axis. The central block of each tower was in the horizontal plane including the beam axis, while the other two blocks formed an angle of $\pm 22°$ with the horizontal plane. The distance between the target and the front face of the blocks was 138 cm. In this configuration a solid angle of 4.8% of 4π was covered, but the analysis was restricted to a more narrow rapidity range, $0.510 \leqslant y \leqslant 0.718$, centered around midrapidity ($y = 0.614$). A natural calcium target of 390 mg/cm^2 thick was used. The incident ^{40}Ar beam of $3.5 \cdot 10^7$ particles/s was monitored by a start detector consisting of 32 plastic detectors mounted in two rings around the beam pipe covering polar angles from 15° to 30° and placed at 10.1 cm distance from the target. This detector provided the time-zero signal and was also used to measure the number of reactions and the centrality of the collision.

Two main triggers were implemented in the experiment. The first one, used for π^0 mesons, required two neutral hits with an energy deposit larger than 15 MeV in individual BaF_2 detectors and in two different blocks of TAPS. The second trigger required two hits with an energy larger than 90 MeV in two different blocks, irrespective of the CPV information. This trigger was used to enhance the η-meson content in the data sample. Both triggers, in addition, required the coincidence with a signal from the start detector. The ability of this device to register a reaction depends on

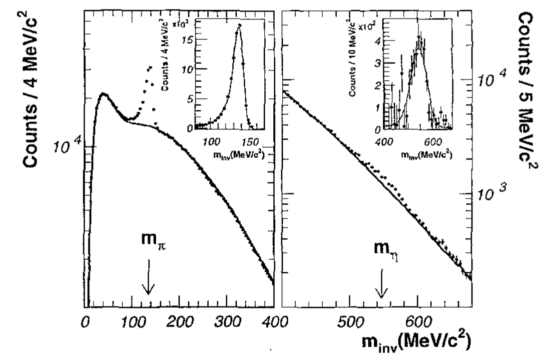

Fig. 1. Invariant-mass spectra (solid points) for the π^0 trigger (left) and for the η trigger (right) together with the mixed-event background (lines). Invariant-mass distributions after background subtraction are shown in the insets, where the lines represent a fit to meson intensities using an asymmetric gaussian, inspired by extensive detector response investigations [26,27].

the number of nucleons and fragments emitted. Therefore, the start detector introduces a bias towards central collisions. However, since requiring hits in TAPS also enhances central events, the additional presence of the start detector in the trigger condition increases the selectivity only slightly. The resulting bias on the trigger level has been investigated by analyzing events collected under the condition of only two neutral hits with more than 15 MeV in TAPS. Comparing the number of pions observed in coincidence with and without the start detector we find that the loss of π^0 yield is 5%, while the loss of η yield is negligible under the conditions of the η trigger described above, which is already more selective to central collisions due to the requirement of higher energies in TAPS.

Photons were discriminated from massive particles by time-of-flight, by pulse-shape analysis and by the use of the veto detectors [6]. The π^0 and η mesons were identified in the two-photon invariant-mass spectrum (Fig. 1) constructed from all photon pairs detected in TAPS. The invariant mass is given by $m_{\mathrm{inv}} = \sqrt{2E_1E_2(1-\cos\theta_{12})}$, where $E_{1,2}$ are the photon energies and θ_{12} is their opening angle in the laboratory frame. The meson signals appear as peaks at their rest mass (135.0 MeV/c^2 and 547.5 MeV/c^2, respectively) on top of a combinatorial background, which is due to the fact that the probability to produce more than one π^0 meson is sizeable for this beam energy. The combinatorial background (Fig. 1) was determined by the event-mixing technique [7].

Event classes defined by the transverse momentum of the pair and by the photon multiplicity were treated separately to assure that the phase-space distribution of mixed and real pairs was the same [8].

The total π°- and η-meson yields were obtained by integrating the invariant-mass ranges 100–150 MeV/c^2 and 450–600 MeV/c^2, respectively, and subtracting the background in the rapidity range covered by TAPS. Meson multiplicities are defined as $\langle M^{\Delta y}_{\pi^\circ,\eta}\rangle = n_{\pi^\circ,\eta}/n_{\text{reactions}}$, where $n_{\pi^\circ,\eta}$ is the number of measured mesons and $n_{\text{reactions}}$ is the number of reactions detected by the start detector, both being corrected for dead time and efficiency. Start detector and TAPS efficiencies for reaction and meson detection, respectively, were determined by Monte Carlo simulations performed with the GEANT code [9]. In the case of the start detector efficiency events calculated by the IQMD model were used as input [10]. Fragment formation was taken into account by using the minimum spanning procedure as described by Peilert et al. [11]. The efficiency of the start detector was found to be 64% on the average, being 20% in the case of peripheral reactions (b = 7 fm) and 100% for central ones (b < 3 fm). To determine the acceptance of TAPS a thermal and isotropic source of mesons at midrapidity was used with the temperature given by the inverse slope parameters experimentally measured. This source was also taken for the extrapolation of meson multiplicities to the full solid angle. Inclusive meson-production probabilities per participant nucleon were determined from meson multiplicities using $P^{\text{incl}}_{\pi^\circ,\eta} = \langle M^{4\pi}_{\pi^\circ,\eta}\rangle/\langle A_{\text{part}}\rangle$, where the minimum bias value $\langle A_{\text{part}}\rangle = 20$ is taken from a geometrical model by Cugnon et al. [12]. Cross sections were obtained from meson multiplicities by $\sigma_{\pi^\circ,\eta} = \langle M^{4\pi}_{\pi^\circ,\eta}\rangle \cdot \sigma_R$, where σ_R is calculated from $\sigma_R = \pi \cdot (1.14)^2 \cdot (A_p^{1/3} + A_t^{1/3})^2$ fm^2 = 1.91 b. The quantities A_p and A_t are the mass numbers of target and projectile, respectively. The choice of the radius parameter r_0 = 1.14 fm is consistent with the measured reaction cross section reported in [13]. The results are listed in Table 1. The ratio η/π° is $(7.1 \pm 0.8)\cdot 10^{-3}$ for the rapidity range selected in the analysis and $(4.1 \pm 0.4)\cdot 10^{-3}$ after extrapolation to 4π.

Transverse-momentum distributions were obtained as the difference between the distributions gated on the meson peaks in the invariant-mass spectrum and the corresponding mixed-event distributions normalized to the combinatorial background under these peaks. In addition, the spectra were corrected for the TAPS acceptance determined in a GEANT simulation. The resulting π° and η transverse-momentum distributions were fitted using $d\sigma/dp_t \propto p_t\, m_t\, \exp(-m_t/T)$ with $m_t = \sqrt{m^2 + p_t^2}$, which is a valid approximation for a Boltzmann distribution in a small rapidity window around midrapidity [14]. Inverse slope parameters of $T_{\pi^\circ} = 55.5 \pm 1.5$ MeV and $T_\eta = 48 \pm 6$ MeV were obtained from the fit. The average transverse momenta extracted from the data are $\langle p_{t,\pi^\circ}\rangle = 176 \pm 4$ MeV/c and $\langle p_{t,\eta}\rangle = 235 \pm 15$ MeV/c. Our observation that the data can be fairly well described by only one inverse slope parameter is consistent with Refs. [15–19]. There it was found that a combination of two Boltzmann distributions is only needed for heavier nucleus-nucleus systems or higher bombarding energies. The inclusive π° and η inverse slope parameters are identical within the experimental errors, while the mean value of $\langle p_t\rangle$ is larger for η mesons.

Fig. 2 shows the measured cross section within the rapidity interval around midrapidity in a representation of $1/m_t^2 d\sigma/dm_t$ as a function of the transverse mass. For $m_t > m_\eta$ the π° and η cross sections are identical within our experimental uncertainties. This phenomenon known as m_t scaling has been previously

Table 1
Meson multiplicities and cross sections in the rapidity range $0.510 \leqslant y \leqslant 0.718$ for the reaction ^{40}Ar + $^{\text{nat}}$Ca at 800A MeV. The cross sections are calculated using the reaction cross section of σ_R = 1.91 b [13]. Values extrapolated to the full solid angle are also given as well as the inclusive production probabilities P^{incl}. The inverse slope parameters T and the averaged transverse momenta $\langle p_t\rangle$ extracted from spectral distributions are listed. The last line shows the meson multiplicities from a BUU calculation for the experimental rapidity range

	π°	η
$\langle M^{\Delta y}\rangle$	$(9.9\pm1.5)\cdot10^{-2}$	$(7.0\pm1.5)\cdot10^{-4}$
$\sigma^{\Delta y}$ (mb)	190±30	1.3±0.3
$\langle M^{4\pi}\rangle$	0.62±0.09	$(2.5\pm0.6)\cdot10^{-3}$
$\sigma^{4\pi}$ (b)	1.18±0.17	$(4.8\pm1.1)\cdot10^{-3}$
P^{incl}	$(3.1\pm0.5)\cdot10^{-2}$	$(1.3\pm0.3)\cdot10^{-4}$
T (MeV)	55.5±1.5	48±6
$\langle p_t\rangle$ (MeV/c)	176±4	235±15
$\langle M^{\Delta y}_{\text{BUU}}\rangle$	$(8.76\pm0.09)\cdot10^{-2}$	$(3.3\pm0.5)\cdot10^{-4}$

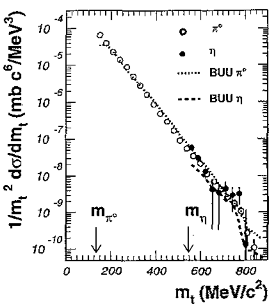

Fig. 2. Transverse-mass distributions for π^0 (open symbols) and η (closed symbols) mesons in the rapidity range $0.510 \leqslant y \leqslant 0.718$. Dotted and dashed lines represent the results from a BUU calculation for π^0 and η mesons, respectively. The statistical errors are negligible in case of π^0 mesons and of the order of 15% for η mesons.

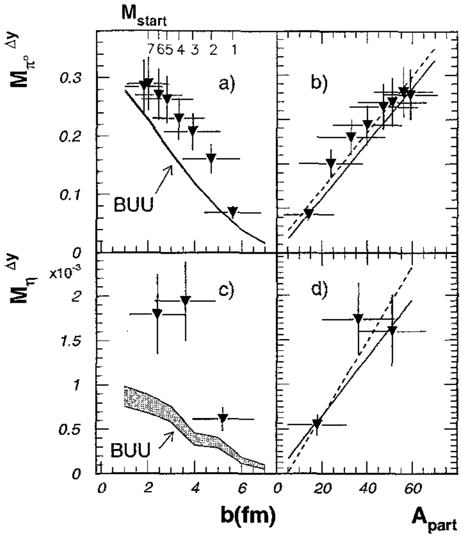

Fig. 3. The two left frames (a) and (c) show experimental π^0 and η meson multiplicities in the rapidity interval selected in the analysis $M^{\Delta y}_{\pi^0,\eta}$ as a function of the impact parameter. The shaded areas represent the BUU meson multiplicities with statistical errors. The π^0 and η meson multiplicities extrapolated to the full solid angle $M^{4\pi}_{\pi^0,\eta}$ are shown as a function of the number of participant nucleons in the two right frames (b) and (d), respectively. The continuous lines are given by $M^{4\pi}_{\pi^0,\eta} = P^{\rm incl}_{\pi^0,\eta} \cdot A_{\rm part}(b)$, where $P^{\rm incl}_{\pi^0,\eta}$ is deduced from the inclusive meson multiplicities and $A_{\rm part}(b)$ is given by the geometrical model of Gosset et al. [20]. The dashed lines are linear fits to the exclusive data.

observed for the same system at higher energies [2]. Our data extend the validity of m_t scaling down to 800A MeV for medium size systems. The scaling indicates that the energy required to produce a given transverse mass is the important parameter determining the relative abundance of the two meson species [2], even at bombarding energies as low as 2/3 of the η-meson production threshold in free nucleon-nucleon collisions.

As the maximum nuclear-matter density reached during the collision depends on the impact parameter, it is of great importance to obtain exclusive meson-production cross sections. In our experiment the particle multiplicity in the start detector depends on the impact parameter of the collision. The relation between the multiplicity in the start detector and the impact parameter was established in the simulation of the start detector response, as previously described. We have calculated the number of participant nucleons by averaging over the distribution of impact parameters corresponding to a given start detector multiplicity and using the parameterization of Gosset et al. [20] to calculate the participant number corresponding to a given impact parameter. The π^0- and η-meson multiplicities as a function of the impact parameter in the collision are shown in Fig. 3 for the rapidity range selected in the analysis. Extrapolations of these values to the full solid angle as a function of the number of participants are shown in the same figure. An increase of π^0- and η-meson multiplicities with the number of participant nucleons is observed. This increase is directly proportional to $A_{\rm part}$ in the case of $M^{4\pi}_{\pi^0}$ as shown by the fit of Fig. 3. The identical fit procedure suggests proportionality also for the η multiplicity $M^{4\pi}_{\eta}$, albeit with larger uncertainty. This increase reflects a constant meson-emission probability per participant nucleon. Direct proportionality has been previously observed for pions [13,19,21] but now, for the first time, the same result is obtained for subthreshold η-meson production in a medium-size system. It is interesting to study the ratio η/π^0 as a function of impact parameter because the ratio is less sensitive to systematic uncertainties. A variation of η/π^0 would indicate different production mechanisms for π^0 mesons versus η mesons. Moreover, differences in the meson ratio as a function of the number of participants could eventually influence the m_t scaling. Values of this ratio are listed in Table 2. No dependence of the ratio η/π^0 on the impact parameter of the collision is observed for the ^{40}Ar+$^{\rm nat}$Ca system within the experimental uncertainty.

Table 2
Ratio η/π° for different multiplicities in the start detector. The corresponding impact parameters have been calculated with a simulation (see text)

M_{start}	b (fm)	$(\eta/\pi^{\circ})^{\Delta y}$
1–2	5.2±1.3	$(6.2\pm1.7)\cdot 10^{-3}$
3–4	3.6±1.3	$(9.0\pm2.5)\cdot 10^{-3}$
>4	2.4±1.2	$(6.6\pm2.0)\cdot 10^{-3}$

The experimental results were compared to the predictions of the BUU model in the version implemented by Wolf et al. [22]. The microscopic transport-model calculations describe heavy-ion reactions as a sequence of nucleon-nucleon collisions taking mean-field effects into account. The inclusive π°- and η-meson multiplicities obtained with the BUU model are listed in Table 1 for the rapidity range selected in the analysis. The BUU calculation slightly underestimates the experimental π° meson multiplicity, whereas the theoretical prediction for the η meson multiplicity is about a factor 2 smaller than our data. It should be noted, however, that this factor is within the uncertainties of the elementary η cross sections used in BUU. The π° and η transverse-mass distributions obtained with the BUU model are shown in Fig. 2 together with the experimental ones. The theoretical π° distribution is in good agreement with the data except for very low m_t values, where the failure of BUU might be due to the lack of high resonances with two pion decay channels in the present model calculations [23]. In the case of the η mesons, the theoretical distribution reproduces the slope of the spectrum but fails to give the absolute magnitude as already mentioned above.

In Fig. 3, π°- and η-meson multiplicities extracted from the BUU model are presented as a function of impact parameter. The BUU model underestimates slightly the experimental π°-meson multiplicities. In case of η mesons, BUU fails to reproduce the experimental values by roughly a factor 2 giving rise to the discrepancy observed for the inclusive η meson multiplicity. Besides the problem of the poorly known production cross sections this behaviour could be also due to the way in which production and absorption are taken into account in BUU. So far, only two-body processes have been considered, but also processes with several nucleons involved might be important.

The number of $\Delta(1232)$ and N(1535) resonances in the high-density stage of the collision can be determined from the experimental neutral meson yields taking the meson-to-resonance ratio from the BUU model, where only those mesons which escape from the nuclei have been considered ($\pi/\Delta(1232) = 0.96 \pm 0.05$ and $\eta/\mathrm{N}(1535) = 0.43 \pm 0.09$). The BUU prediction for π/π° is very close to 3 in agreement with the experimental charged pion cross sections for the system Ar+KCl at 800A MeV [24]. Employing the asymptotic meson-to-resonance ratios and the π/π° ratio from BUU one would obtain population probabilities in the high-density phase of $(9.7 \pm 1.6)\cdot 10^{-2}$ and $(3.0 \pm 0.9)\cdot 10^{-4}$ for the $\Delta(1232)$ and N(1535) resonances, respectively. With the additional information from BUU that the maximum density reached in the collision averaged over all impact parameters is $\rho_{\max} = (2.0 \pm 0.3)\rho_0$, a density of $\Delta(1232)$ resonances of $\rho_{\Delta} = (0.19 \pm 0.04)\rho_0$ is obtained. This density of $\Delta(1232)$ resonances shows that a substantial part of the energy available in the collision is used to excite resonances, i.e. internal degrees of freedom. The knowledge of the density of resonances is necessary in order to establish the evolution of the baryonic composition of nuclear matter from its normal state to resonance matter.

In summary, η-meson production at a bombarding energy of only 2/3 of the threshold energy in free nucleon-nucleon collisions was studied for the system ^{40}Ar + $^{\mathrm{nat}}$Ca. The inclusive η-meson production probability obtained confirms the systematics provided by previous measurements [1,2]. The energy dependence of η-meson production, for instance, is an important ingredient to obtain the Dalitz decay contribution $\eta \to e^+e^-\gamma$ to the dilepton invariant mass spectra [25]. For the first time exclusive results on η mesons are shown simultaneously with π° meson data. An increase of both meson multiplicities proportional to the number of participant nucleons is observed. The BUU calculation reproduces the experimental results for π° mesons, whereas the theoretical predictions are smaller than the experimental values for η mesons. In particular, the m_t scaling is shown to be partially reproduced by the BUU model. From the experimental π°- and η-meson production probabilities, information about the baryonic composition of the excited nuclear matter in the high-density phase of the collision is estimated based on BUU. The resulting density of

$\Delta(1232)$ resonances extracted from the π^0 production probability is an indication of the evolution of the collision zone towards resonance matter.

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